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MEASUREMENT OF KNOCK CHARACTERISTICS IN SPARK-IGNITION ENGINES

By R. Schütz

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MEASUREMENT OF KNOCK CHARACTERISTICS IN SPARK-IGNITION ENGINES*

By R. Schütz

The very fact that no simple and yet reliable test method is available renders the measurement of the knock characteristics of Otto engines or of fuels extremely difficult.

The bouncing-pin indicators commercially available at present (fig. 1) utilize the pressure in the combustion chamber to deflect a built-in membrane and at the same time force a loose pin on the membrane into motion. The speed at which the pin rises equals the speed of the contact point of the membrane so long as it is not retarded. At the instant of decreasing membrane speed, i.e., the moment at which the rate of pressure rise in the combustion chamber reaches a maximum, the pin is released and continues of its own accord. On reaching a certain height a switch closes an electric circuit, and opens it again as soon as the pin drops. The time interval of the current flow is recorded by thermotransformer.

According to the foregoing, i.e., the ideal case, it is dependent upon:

1) The speed at which the pin has left the membrane, i.e., in the ideal case, on the maximum rate of pressure rise in the cylinder $\left(\frac{dp}{d\alpha}\right)_{max}$;

2) The amount of membrane curvature at the instant of separation of pin and membrane, i.e., in the ideal case, on the terminal combustion pressure.

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*"Über die Messung der Klopffestigkeit an Ottomotoren." A.T.Z., vol. 42, no. 13, July 10, 1939, pp. 364-370.

In reality there are many other effects besides those cited here. To begin with, the pin itself must drop back again on the membrane. This renewed contact engenders a shock, i.e., the pin makes a sudden jump and, under certain conditions, closes the circuit again. This new time interval itself is dependent upon

3) The rate of contact between pin and membrane which, the power stroke having started, consists of the speed of the pin less the velocity of the membrane. But the latter is now dependent upon the rate of pressure drop, ie., the expansion.

The performance usually repeats itself several times until at last the jumps become so small as a result of friction and impact loss that the contacts no longer touch, although there is no complete rest before the start of the new cycle.

Aside from these three factors which in any case still have something to do with the combustion process, there are yet several other effects as definite sources of errors. Figure 2 illustrates the time rate of change of contact between pin and membrane for three cycles. First, it is apparent that the pin often leaves the membrane during a cycle and that the number of jumps differs substantially for different cycles. For instance, they amounted to 15 and 56 jumps for two successive cycles with respect to time, whereas the test engine operated under perfectly steady conditions. Another surprising fact is the marked scattering of the diagram points which is indicative of a renewed contact followed by shock process. Since the presented tension drop in the contact point depends upon the closeness of contact it is anticipated that the diagram points for renewed contact fall on a curve of uniform variation. The profound disturbance, chiefly at the right below, is due to the natural oscillation of the membrane. Since the relative speed between pin and membrane is of decisive importance at impact, it cannot be immaterial whether contact is made just when the membrane swings downward and the next time upward. A simple approximation gives for the thus incurred error an order of magnitude of ±40 percent relative to the initial speed of the pin. The error can also occur with the very first jumping motion because the natural oscillation of the membrane usually does not die out completely or is already excited again at start of combustion.

Figure 3 illustrates the bouncing-pin motions for six cycles at slightly knocking operation. Quite surprising are the great differences at the highest jumps, for example, cycle IV and VI. The cause lies in the natural oscillation of the membrane and in the differences in the combustion process for the individual working cycles, as explained briefly later on. Note also the baffling scatter in the second and third jumps, for example, cycle II and VI, due solely to the natural oscillation of the membrane.

As a further source of error, mention is made of the shock process between the two test contacts; it produces an oscillation of the upper contact spring and consequently, undesired interruptions in the current flow. Figure 4 shows the touching intervals of the test contacts for a cycle at moderately knocking combustion. It is plainly seen that the pin jumped four times, lasting up to closing of contact. The four separate touching periods become shorter with time and have approximately the expected aspect. However, even this exceptionally plain diagram reveals the effect of the natural vibrations of the constant springs, since the flow of current in the individual touching periods is several times interrupted following the deflection of the upper contact. Figure 5 repeats the same process for a more severe knocking combustion. In this instance the defective effect of the natural oscillations of membrane and contact springs is so profound as to obliterate every trace of uniformity. In common measurements with modern bouncing-pin indicators, this picture represents about a normal case, while the foregoing constitutes a rare, noteworthy exception. On comparing the two pictures, it becomes evident that the bouncing-pin indicator often records the less severe knock for the more easily knocking fuel.

Lastly, there is the danger of burned contacts, which naturally increases with the number of current interruptions. Figure 6 shows one of the previously carefully ground contacts after 3-1/2 hours of operation. Obviously such rapid changes in contact characteristics is not permissible in a testing device.

Following the discussion of these three potential sources of error, we call attention to various results which make the bouncing-pin indicator appear fundamentally unsuitable for recording knock phenomena.

A. In figure 7, the pressure-path diagrams for two successive cycles are presented. This graph also shows clearly that a certain scatter of the test data is to be expected, because the individual combustion processes are dissimilar. Both cases show that, before incipient knock, which lies at around B, a maximum of the rate of pressure rise had already been exceeded at around B, i.e., the bouncing pin has left the membrane at A before the knocking combustion had even begun. For such, not at all seldom cases, the test result has therefore nothing to do with knocking.

B. Up to the present time it has never been definitely established that the maximum rate of pressure rise in the engine is an absolute criterion for the severity of the knock. According to figure 8, which, together with the following text, has been taken from Ricardo's "High-Speed Internal Combustion Engines," just the opposite appears to be correct. This is also confirmed by figure 9, where the values for the maximum rate of pressure rise is shown for two fuel blends of about 12 octane number difference. The length of each vertical dash gives the value for the maximum $\frac{dp}{d\alpha}$ for a certain cycle, as recorded with piezoelectric indicator and differentiation instrument. If the maximum $\frac{dp}{d\alpha}$ were an unobjectionable criterion for the severity of the knock, the dashes for the fuel on the left would have to be definitely longer than for the fuel at the right.

C. That the terminal pressure of combustion is not definitely determined by the severity of the knock is general knowledge.

D. Nothing was found to support the assumption that rate of pressure drop in the power stroke (expansion) depends upon the severity of the knock; moreover, there are hardly any reasons for it.

The chapter "Bouncing-Pin Indicators" is closed with the brief notation that the test data were obtained for

1) The maximum rate of pressure rise $\left(\frac{dp}{d\alpha}\right)_{max}$,

2) The terminal pressure of combustion (p_{max}),

3) The rate of pressure drop (expansion cycle).

Inasmuch as none of these three factors is definitely associated with the knock process, it is difficult to see how the total result could reproduce the knock intensity correctly.

Quite apart from that, the bouncing-pin indicator readings are adversely affected by the

1) Natural oscillations of the membrane,

2) Natural oscillation of the contact springs,

3) Burned spots on the contact points,

4) Unusual combustion aspect,

which confirms more than ever the unsuitability of the bouncing-pin indicator as dependable recording instrument.

Before proceeding to the findings and test methods which might be suitable as substitutes for the bouncing pin, a brief account of the combustion and knocking in the spark-ignition engine is given.

The compressed charge is ignited by the spark plug at a point, a flame front comes into being which advances somewhat like a ball in every direction. The rate of advance of this flame front differs for different fuels and for different excess air factors within certain limits and usually - but not always - increases definitely with the pressure and temperature. The burning portions of the charge induce a pressure and temperature rise of the part of the charge not yet reached by the flame front, until under the circumstances, the conditions of autoignition are given. If these conditions occur, the knocking combustion begins, i.e., the still non-burning portion of the charge rapidly develops numerous new igniting spots from which in turn ball-like flame fronts emanate. Then the rise in the rate of advance of the flame front is actually more apparent than real because of the appearance of the many new ignition spots. Visualizing - what perhaps comes close to the truth - that at incipient knock, i.e., on reaching the conditions of autoignition, within a very short time one new ignition spot appears right next to the other, then the new flame fronts have to travel no distance. The result is an apparently infinitely high flame speed and the incipient knock becomes at the same time the end of the combustion; followed by an instantaneous release of the total energy of the part of the charge not yet reached by the original flame front at incipient knocking. This free energy creates a sudden local pressure peak which equalizes itself as pressure wave. The pressure wave in turn speeds through the combustion chamber at sonic - hence finite - velocity. The starting point of the pressure wave or "knock oscillations" is the center of gravity of the energy - or in homogeneous mixture the spatial center of gravity - of the part of the charge not yet reached by the original flame front at incipient knock. The knock intensity is above all governed by the part of the charge that must burn so as to create the auto-ignition conditions for the residuary charge. If these viewpoints are correct, the knock characteristics can be determined in the following manner:

1) By determination of the oscillation amplitude of the knock frequency, because, the greater the portion of the charge which burns only after the conditions of autoignition have been reached, the stronger the developed pressure wave and the higher the oscillation amplitude of the knock frequency.

2) By determination of the time interval by which two quartz pick-ups indicate the start of the knock frequency differently. Assuming uniform sonic velocity throughout the whole combustion chamber the simultaneous use of several quartz chambers affords the local position of the knock center and hence the amount of the charge portion that burns after appearance of the autoignition conditions and defines the knock intensity.

3) By determining the combustion time. Assuming the end of the combustion to coincide with the incipient knock, one can definitely ascertain whether a cylinder knocks or not. As in the part of the charge with knocking combustion, an apparently infinite flame speed is reached, the combustion time changes rapidly,

Note 1. Determination of oscillation amplitude.- Figure 10 illustrates the frequency distribution in a pressure chart for different knock intensities. As the knock increases, the values for some frequency zones rise materially (for instance, No. 3: 50-64Hz, No. 5: 80-100 Hz), while for others it is much less (No. 4: 64-80Hz, No. 6: 100-125Hz, No. 8: 160-200Hz). One particularly noteworthy feature is the rise of the values for the frequency zone No. 22: 4000-5000Hz, while the increasing knock strength to frequencies of 800-3200Hz has no effect whatsoever. Hence the suggestion that the knock frequency falls into zone No. 22 or one near to it. Unfortunately the experimental lay-out did not suffice for still higher frequencies, so that the chart stops at the most interesting part. Figure 11 shows the values for some frequency groups plotted against the fuel level in the carburetor of the I.G. test engine, i.e., against the excess air factor. The frequency zone No. 23 comprises all those above 4000Hz. On comparison with the mean temperature curve, which is also shown, it can be seen that the values for the frequency zone No. 23 reproduce the knock strength soonest. This means that the knock frequency for the employed test engine at 600 rpm lies above 4000Hz. Exactly determined, it was 6500Hz. The knock is, in fact, quite accurately reproduced by its oscillation amplitude, but unfortunately this method is not simple enough to warrant its use for general operating measurements, because the knock oscillation fluctuates in its frequency and oscillation amplitude for different fuels and knock intensities. In consequence, it is difficult to form exact average values and at the same time to assure sufficient measuring accuracy in simple fashion.

Note 2. Determination of incipient knock oscillation.- Figure 12 shows the cylinder head of an I.G. test engine with two quartz pick-ups and spark plug. Each quartz chamber operates across an amplifier and a filter, which cuts off all frequencies below 4000Hz, on a beam of a twin-beam lamp, so that the knock oscillation is recorded by each chamber. The two oscillations are timed different, as figure 13 shows, when the knock center, that is, the starting point of the pressure wave is not equally distant from the two quartz chambers. In this way, it is possible to determine the location of the knock center, if the height of the combustion chamber is neglected. If the distance of the starting point of the pressure wave from the bottom of the piston itself is desired, then a third quartz chamber becomes necessary. In this manner, it is possible to study the effect of overheated spots in the walls of the combustion chamber. For fuel research, this method offers notable prospects.

The recorded time differences obtained for different fuels under otherwise identical operating conditions afford a satisfactory survey, as figure 14 indicates. The scattering of the individual test points in this picture was to be expected, since each test point was determined from a single operating cycle. So, instead of average values, these are individual measurements which must scatter, for the very reason that the combustion processes for the individual operating cycles are different, as already indicated. By forming an average over a greater number of cycles, with some kind of a test set-up as, for instance, is indicated in figure 17, fairly practical results can be obtained.

The recording of the incipient knock oscillation, say in degrees of crank setting, with only one quartz chamber, gives rough reference values for the knock intensity, but restricts the accuracy severely, because the time which the pressure wave consumes to spread from the knock center to the quartz chamber enters as a measuring error.

<u>Note 3. Determination of combustion time</u>.- Figure 15 shows a cylinder head of the I.G. test engine with two ionization gaps, spark plug, and a quartz chamber, which, however, served merely for check tests. From the point of view of greatest accuracy as well as possibility of predicting combustion periods in normal, i.e., non-knocking, operation, the ionization gap I should be located as close as possible to the spark plug, and gap II as far away from it as possible. The determination of the instability of the combustion periods due to knocking combustion is contingent upon the original flame front still being between the two ionization gaps while the autoignition conditions are reached. Figure 16 shows the time rate of the voltage drop caused by the ionization gaps during a cycle. Since the ionization gaps are responsive to the high combustion temperatures, the voltage drop becomes suddenly very small when reached by the flame.

Figure 17 illustrates a test circuit for determining the combustion periods. The abrupt voltage change produced when the flame reaches ionization gap I - i.e., at incipient combustion - ignites a grid controlled glow tube A previously cut off by a negative grid bias. The constant B current, not affected by changes in grid voltage, heats resistance 1. Then glow tube B is ignited by ionization gap II, thus heating resistance 2. Then both circuits are simultaneously opened by switch S which is actuated from the crankshaft. Since both circuits are tuned for equal current flows, the temperature difference between resistances 1 and 2 is an indication of the time by which ionization gap II lags behind gap I. But that is the very time lapse of the flame for passing from ionization gap I to II. The temperature difference between the resistances 1 and 2 is recorded by thermocouple with the hot junction at a and the cold junction at b. Thus the deflection of the millivoltmeter is proportional to the combustion time, it records average values. Figure 18 gives the results for various fuels. One important fact brought out is the sudden change in combustion time at a certain compression ratio of all fuels, or in other words, that in this manner it is possible to ascertain the compression ratio of any fuel at which autoignition conditions are reached and beginning at which part of the charge is burned with knocking.

For an appraisal, it certainly is important to know the compression ratio at which the bend in the curve occurs. It indicates the allowable height of compression before the knock limit is reached. Then the angle formed by the two branches in the bend itself appears to be of importance. It is to be expected that it supplies important reference points for the knock tendency of the fuel. This question is now being investigated by the Institute for Automotive Engineering of the Dresden T.S., whose findings are to be published in the very near future.

Figure 19 illustrates the results for a benzine, a benzol, and a benzine-benzol mixture. It is plain that the location of the bend as well as the afore-mentioned angle changes. In fundamentally the same manner, it is possible, of course, to predict the effect of spark advance on the knock, as is indicated in figure 20.

The lay-out, (fig. 21) was used to determine the scatter of incipient combustion and of ignition toward the top center. In these tests the glow tube was tripped by the spark-plug voltage or the ionization gap right next to the spark plug, while the switch S was always opened at the same crank setting. The tests revealed that the mean values for incipient ignition and incipient combustion have no measurable differences.

In consequence, it seems logical to define the combustion time by the determination of the combustion end only, because the incipient combustion itself does not measurably change.

Figure 22 indicates the fundamental course of the test data obtained with this equipment. Theydiffer from those shown before only by a deducted constant and the fact that the combustion time was recorded - at constant speed in degree crank setting - clockwise and again anti-clockwise.

The principal advantages of the last-described test equipment accrue from its single ionization gap, i.e., it requires only one hole in the cylinder head, and its simplicity.

The advantage of the test method itself consists in making it possible to ascertain whether an engine or a certain cylinder of an engine knocks or not, and that the thus-obtained knock-limit values are substantially more accurate and dependable than those obtained by other methods. The prediction of the charge portion which burns knocking and defines the knock intensity, is very easily possible, if the combustion time is measured for different compression ratios or ignition advances.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

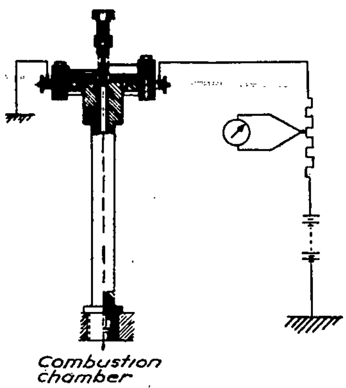

Figure 1.- Bouncing-pin indicator.

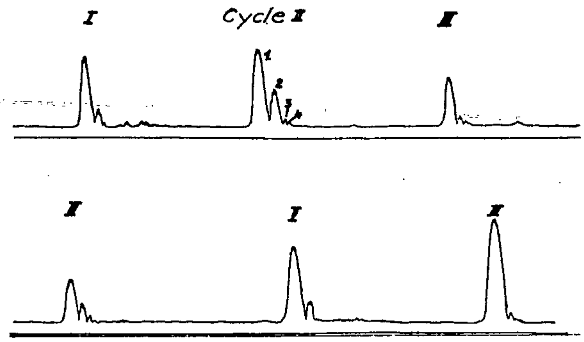

Figure 3.- Motion of bouncing pin.

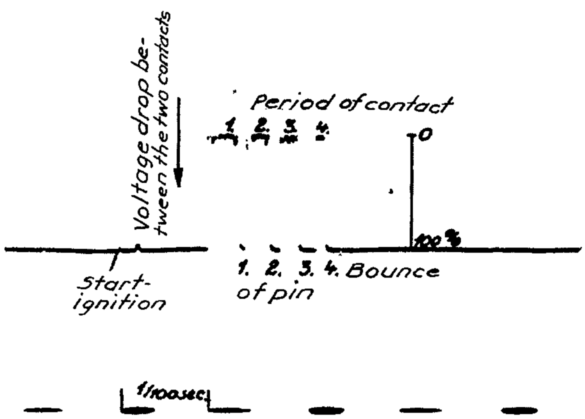

Figure 4.- Touching of test contacts for moderate knock.

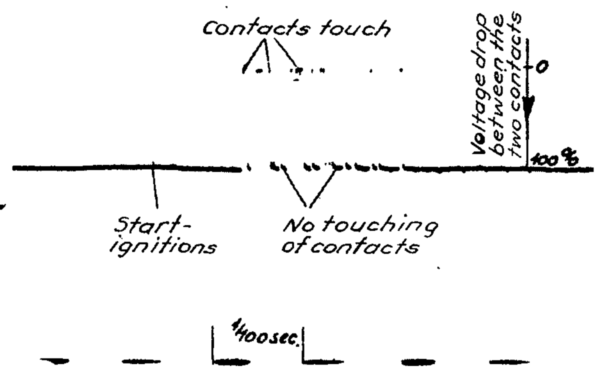

Figure 5.- Touching of test contacts for severe knock.

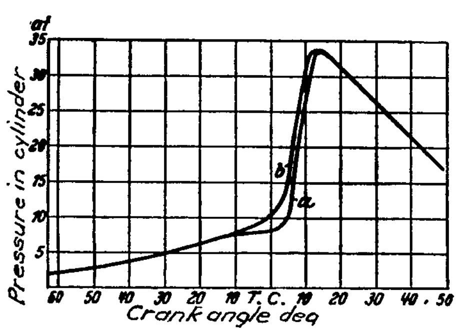

Figure 8.- Pressure cards according to Ricardo.

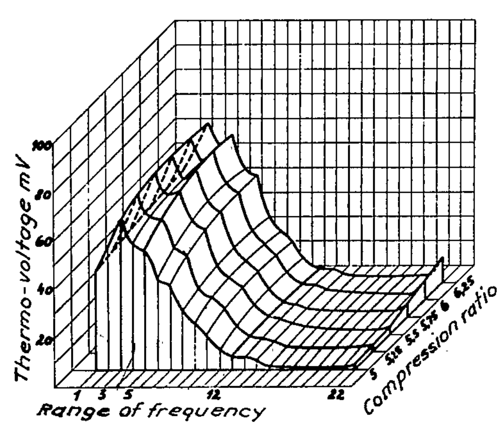

Figure 10.- Frequency distribution in pressure diagram.

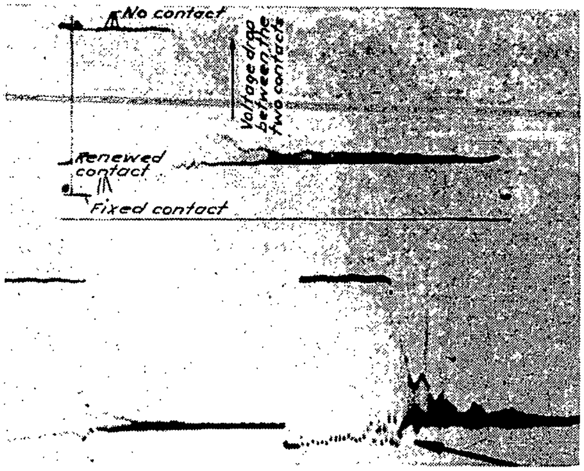

Figure 2.- Contact between bouncing pin and membrane.

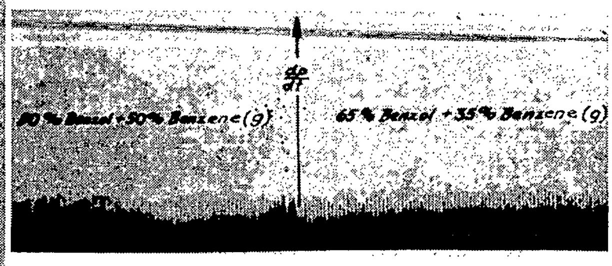

Figure 9.- Maximum rate of pressure rise for different fuels.

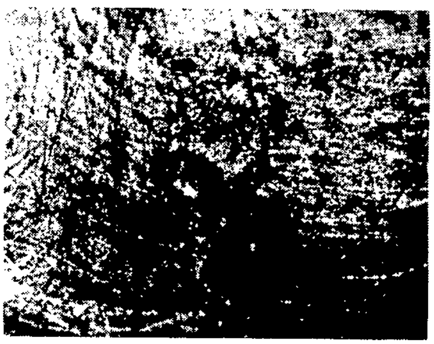

Figure 6.- Contact with burnt spots.

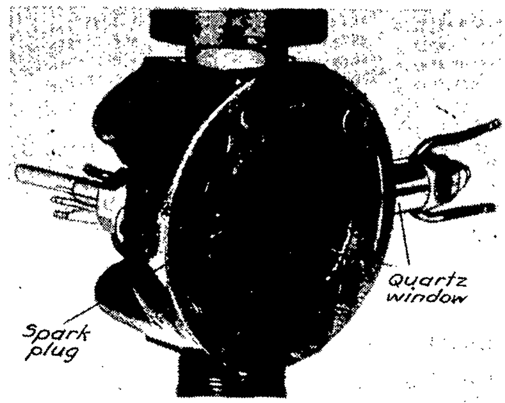

Figure 12.- Quartz chambers in cylinder head.

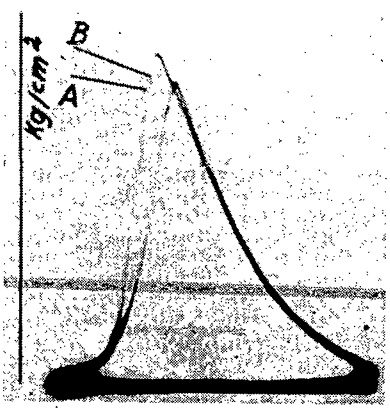

Figure 7.- Pressure cards for knocking combustion.

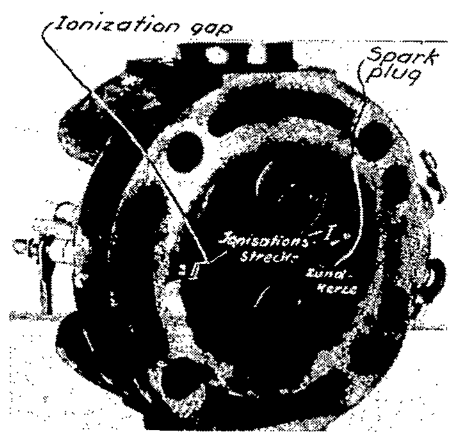

Figure 15.- Ionization gaps in cylinder head.

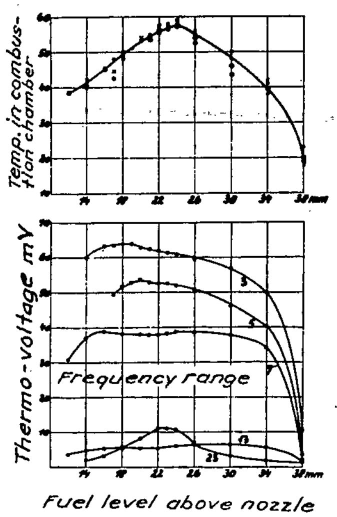

Figure 11.- Frequency distribution by different excess air factors.

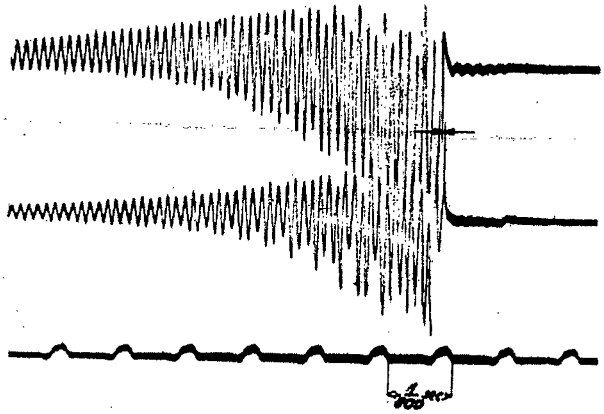

Figure 13.- Knock oscillations.

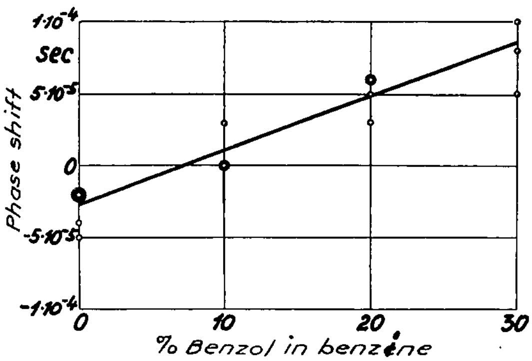

Figure 14.- Phase displacements of knock oscillations.

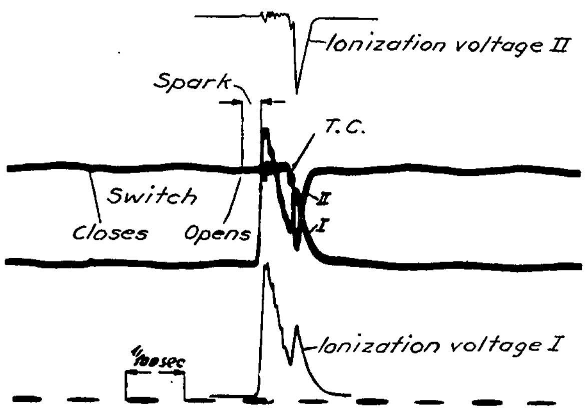

Figure 16.- Ionization diagram.

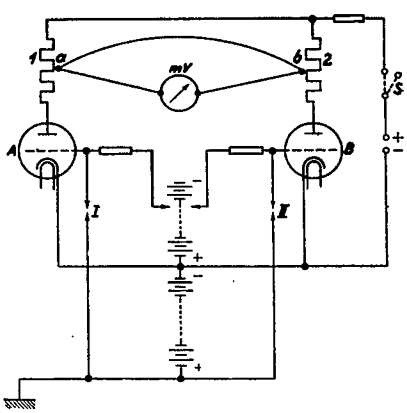

Figure 17.- Set up for recording combustion time.

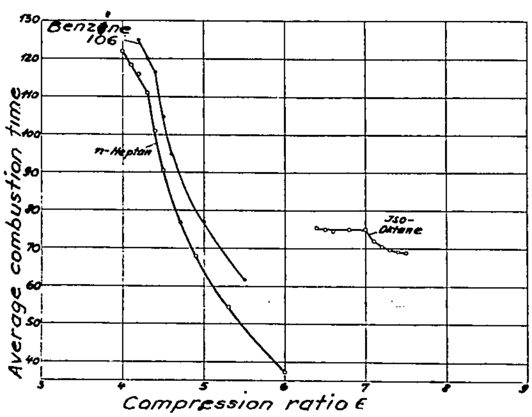

Figure 18.- Combustion time against compression ratio.

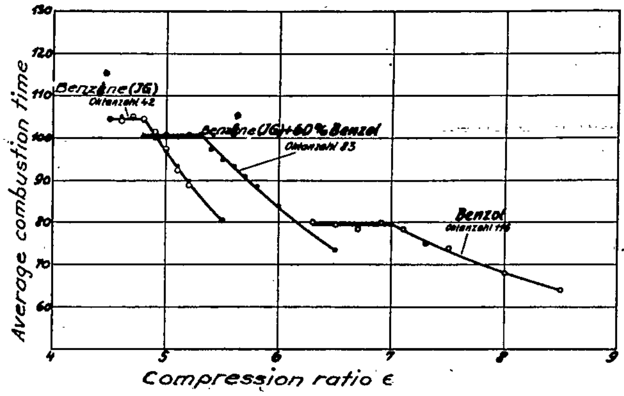

Figure 19.- Combustion time against compression ratio.

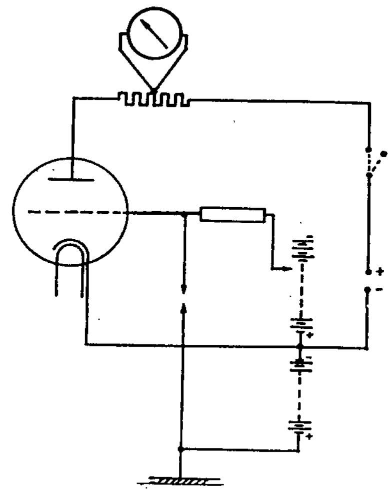

Figure 21.- Hook up for recording combustion time.

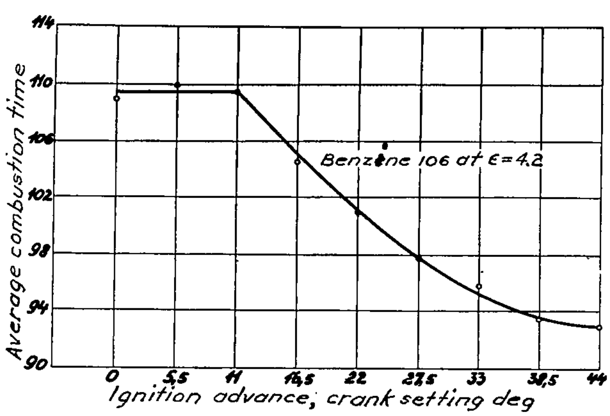

Figure 20.- Combustion time against ignition advance.

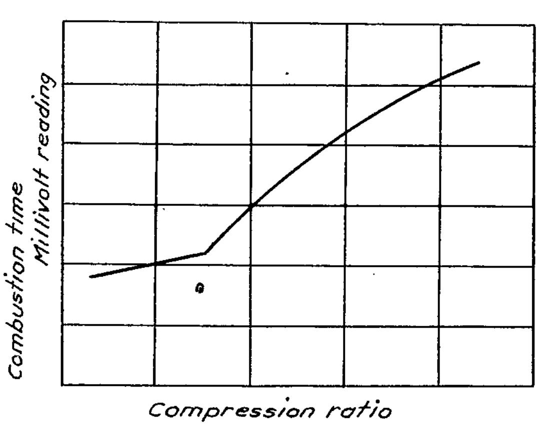

Figure 22.- Combustion time against compression ratio.